

10/584758

Preparation of butadiene

APPROPRIATE TO 27 JUN 2006

Description

[0001] The invention relates to a process for preparing butadiene.

[0002] Butadiene is an important basic chemical and is used, for example, to prepare synthetic rubbers (butadiene homopolymers, styrene-butadiene-rubber or nitrile rubber) or for preparing thermoplastic terpolymers (acrylonitrile-butadiene-styrene copolymers). Butadiene is also converted to sulfolane, chloroprene and 1,4-hexamethylenediamine (via 1,4-dichlorobutene and adiponitrile). Dimerization of butadiene also allows vinylcyclohexene to be generated, which can be dehydrogenated to styrene.

[0003] Just like butadiene, 1-butene is an important basic chemical. Starting from 1-butene, for example, n-valeraldehyde is obtained by the oxo process and hexene by metathesis.

[0004] Butadiene and 1-butene can be prepared by thermally cracking (steamcracking) saturated hydrocarbons, in which case naphtha is typically used as the raw material. In the course of steamcracking of naphtha, a hydrocarbon mixture of methane, ethane, ethene, acetylene, propane, propene, propyne, allene, butenes, butadiene, butynes, methylallene, C₅ and higher hydrocarbons is obtained.

[0005] A disadvantage of the generation of butadiene in the cracking process is that larger amounts of undesired coproducts are inevitably obtained.

[0006] It is an object of the invention to provide a process for preparing butadiene and optionally 1-butene from n-butane, in which coproducts are obtained to a minimal extent.

[0007] The object is achieved by a process for preparing butadiene from n-butane having the steps of

[0008] A) providing a feed gas stream comprising n-butane;

[0009] B) feeding the feed gas stream comprising n-butane into at least one first dehydrogenation zone and nonoxidatively catalytically dehydrogenating

n-butane to obtain a product gas stream b comprising n-butane, 1-butene, 2-butene, butadiene, hydrogen, low-boiling secondary constituents and in some cases steam;

[0010] C) feeding the product gas stream b of the nonoxidative catalytic dehydrogenation and an oxygenous gas into at least one second dehydrogenation zone and oxidatively dehydrogenating 1-butene and 2-butene to obtain a product gas stream c comprising n-butane, 2-butene, butadiene, hydrogen, low-boiling secondary constituents and steam, said product gas stream c having a higher content of butadiene than the product gas stream b;

[0011] D) removing hydrogen, the low-boiling secondary constituents and steam to obtain a C₄ product gas stream d substantially consisting of n-butane, 2-butene and butadiene;

[0012] E) separating the C₄ product gas stream d into a recycle stream e1 consisting substantially of n-butane and 2-butene and a stream e2 consisting substantially of butadiene by extractively distilling and recycling the stream e1 into the first dehydrogenation zone;

[0013] F) if desired, feeding some or all of the stream e2 consisting substantially of butadiene into a selective hydrogenation zone and selectively hydrogenating butadiene to 1- and/or 2-butene to obtain a stream f comprising 1-butene and 2-butene;

[0014] G) if desired, feeding the stream f comprising 1-butene and 2-butene into a distillation zone and removing a product of value stream g1 consisting substantially of 1-butene to leave a stream g2 comprising 2-butene;

[0015] H) if desired, recycling the stream g2 comprising 2-butene into the first or second dehydrogenation zone.

[0016] The process according to the invention features particularly effective utilization of the raw materials. Thus, losses of the n-butane raw material are minimized by recycling unconverted n-butane into the dehydrogenation. The coupling of nonoxidative catalytic dehydrogenation and oxidative dehydrogenation achieves a high butadiene yield. Compared to the generation of butadiene by cracking, the process features high selectivity. No coproducts are obtained. The complicated removal of butadiene from the product gas mixture of the cracking process is dispensed with.

[0017] In a first process part, A, a feed gas stream a comprising n-butane is provided. Typically, the starting raw materials are n-butane-rich gas mixtures such as liquefied petroleum gas (LPG). LPG comprises substantially saturated C₂-C₅ hydrocarbons. In addition, it also contains methane and traces of C₆⁺ hydrocarbons.

The composition of LPG may vary markedly. Advantageously, the LPG used contains at least 10% by weight of butanes.

[0018] Alternatively, a refined C₄ stream from crackers or refineries may be used.

[0019] In one variant of the process according to the invention, the provision of the dehydrogenation feed gas stream comprising n-butane comprises the steps of

[0020] (A1) providing a liquefied petroleum gas (LPG) stream,

[0021] (A2) removing propane and any methane, ethane and C₅⁺ hydrocarbons (mainly pentanes, additionally hexanes, heptanes, benzene, toluene) from the LPG stream to obtain a stream comprising butanes (n-butane and isobutane),

[0022] (A3) removing isobutane from the stream containing butanes to obtain the feed gas stream comprising n-butane, and, if desired, isomerizing the isobutane removed to give an n-butane/isobutane mixture and recycling the n-butane/isobutane mixture into the isobutane removal.

[0023] Propane and any methane, ethane and C₅⁺ hydrocarbons are removed, for example, in one or more customary rectification columns. For example, in a first column, low boilers (methane, ethane, propane) may be removed overhead and, in a second column, high boilers (C₅⁺ hydrocarbons) may be removed at the bottom of the column. A stream comprising butanes (n-butane and isobutane) is obtained, from which isobutane is removed, for example in a customary rectification column. The remaining stream comprising n-butane is used as the feed gas stream for the downstream butane dehydrogenation.

[0024] The isobutane stream removed is preferably subjected to isomerization. To this end, the stream comprising isobutane is fed into an isomerization reactor. The isomerization of isobutane to n-butane may be carried out as described in GB-A 2 018 815. An n-butane/isobutane mixture is obtained and is fed into the n-butane/isobutane separating column.

[0025] The isobutane stream removed may also be sent to a further use, for example for preparing methacrylic acid, polyisobutene or methyl tert-butyl ether.

[0026] In one process part, B, the feed gas stream comprising n-butane is fed into a dehydrogenation zone and subjected to a nonoxidative catalytic dehydrogenation. In this dehydrogenation, n-butane is partly dehydrogenated in a dehydrogenation reactor over a dehydrogenating catalyst to give 1-butene and 2-butene, although butadiene is also formed. In addition, hydrogen and small amounts of methane, ethane, ethene, propane and propene are obtained. Depending on the method of the dehydrogenation, carbon oxides (CO, CO₂), water and nitrogen may also be present in the product gas mixture of the nonoxidative catalytic n-butane dehydrogenation. Unconverted n-butane is additionally present in the product gas mixture.

[0027] The nonoxidative catalytic n-butane dehydrogenation may be carried out with or without oxygenous gas as a cofeed.

[0028] One feature of the nonoxidative method compared to an oxidative method is the presence of hydrogen in the effluent gas. In the oxidative dehydrogenation, free hydrogen is not formed in substantial amounts.

[0029] The nonoxidative catalytic n-butane dehydrogenation may in principle be carried out in any reactor types and methods disclosed by the prior art. A comparatively comprehensive description of dehydrogenation processes suitable in accordance with the invention is also contained in "Catalytica[®] Studies Division, Oxidative Dehydrogenation and Alternative Dehydrogenation Processes" (Study Number 4192 OD, 1993, 430 Ferguson Drive, Mountain View, California, 94043-5272, USA).

[0030] A suitable reactor form is a fixed bed tubular or tube bundle reactor. In these reactors, the catalyst (dehydrogenation catalyst and, when working with oxygen as the cofeed, optionally a special oxidation catalyst) is disposed as a fixed bed in a reaction tube or in a bundle of reaction tubes. The reaction tubes are customarily heated indirectly by the combustion of a gas, for example a hydrocarbon such as methane, in the space surrounding the reaction tubes. It is favorable to apply this indirect form of heating only to about the first 20 to 30% of the length of the fixed bed and to heat the remaining bed length to the required reaction temperature by the radiant heat released in the course of indirect heating. Customary reaction tube internal diameters are from about 10 to 15 cm. A typical dehydrogenation tube bundle reactor comprises from about 300 to 1000 reaction tubes. The internal temperature in the

reaction tubes typically varies in the range from 300 to 1200°C, preferably in the range from 500 to 1000°C. The working pressure is customarily from 0.5 to 8 bar, frequently from 1 to 2 bar, when a small steam dilution is used (similar to the Linde process for propane dehydrogenation), or else from 3 to 8 bar when using a high steam dilution (similar to the steam active reforming process (STAR process) for dehydrogenating propane or butane of Phillips Petroleum Co., see US 4,902,849, US 4,996,387 and US 5,389,342). Typical gas hourly space velocities (GHSV) are from 500 to 2000 h⁻¹, based on the hydrocarbon used. The catalyst geometry may, for example, be spherical or cylindrical (hollow or solid).

[0031] The nonoxidative catalytic n-butane dehydrogenation may also be carried out using the heterogeneous catalysis in a fluidized bed, as described in Chem. Eng. Sci. 1992 b, 47 (9-11) 2313. Appropriately, two fluidized beds are operated in parallel, of which one is generally in the process of regeneration. The working pressure is typically from 1 to 2 bar, the dehydrogenation temperature generally from 550 to 600°C. The heat required for the dehydrogenation is introduced into the reaction system by preheating the dehydrogenation catalyst to the reaction temperature. The admixing of an oxygenous cofeed allows the preheater to be dispensed with and the required heat to be generated directly in the reactor system by combustion of hydrogen and/or hydrocarbons in the presence of oxygen. Optionally, a hydrogen-containing cofeed may additionally be admixed.

[0032] The nonoxidative catalytic n-butane dehydrogenation may be carried out in a tray reactor with or without oxygenous gas as a cofeed. This reactor comprises one or more successive catalyst beds. The number of catalyst beds may be from 1 to 20, advantageously from 1 to 6, preferably from 1 to 4 and in particular from 1 to 3. The catalyst beds are preferably flowed through radially or axially by the reaction gas. In general, such a tray reactor is operated using a fixed catalyst bed. In the simplest case, the fixed catalyst beds are disposed axially in a shaft furnace reactor or in the annular gaps of concentric cylindrical grids. A shaft furnace reactor corresponds to one tray. Carrying out the dehydrogenation in a single shaft furnace reactor corresponds to a preferred embodiment, in which it is possible to work with oxygenous cofeed. In a further preferred embodiment, the dehydrogenation is carried out in a tray reactor having 3 catalyst beds. In a method without oxygenous gas as cofeed, the reaction gas mixture is subjected to intermediate heating in the tray reactor on its way from one catalyst bed to the next catalyst bed, for example by passing it over heat exchanger

plates heated by hot gases or by passing it through tubes heated by hot combustion gases.

[0033] In a preferred embodiment of the process according to the invention, the nonoxidative catalytic n-butane dehydrogenation is carried out autothermally. To this end, the reaction gas mixture of the n-butane dehydrogenation is additionally admixed with oxygen in at least one reaction zone and the hydrogen and/or hydrocarbon present in the reaction gas mixture is at least partially combusted, which directly generates in the reaction gas mixture at least a portion of the heat required for dehydrogenation in the at least one reaction zone.

[0034] In general, the amount of oxygenous gas added to the reaction gas mixture is selected in such a manner that the amount of heat required for the dehydrogenation of n-butane is generated by the combustion of the hydrogen present in the reaction gas mixture and any hydrocarbons present in the reaction gas mixture and/or carbon present in the form of coke. In general, the total amount of oxygen supplied, based on the total amount of butane, is from 0.001 to 0.5 mol/mol, preferably from 0.005 to 0.2 mol/mol, more preferably from 0.05 to 0.2 mol/mol. Oxygen may be used either as pure oxygen or as an oxygenous gas in the mixture with inert gases, for example in the form of air. The inert gases and the gases resulting from the combustion generally provide additional dilution and therefore promote the heterogeneously catalyzed dehydrogenation.

[0035] The hydrogen combusted to generate heat is the hydrogen formed in the catalytic n-butane dehydrogenation and also any hydrogen additionally added to the reaction gas mixture as hydrogenous gas. The amount of hydrogen present should preferably be such that the H_2/O_2 molar ratio in the reaction gas mixture immediately after the oxygen is fed in is from 1 to 10 mol/mol, preferably from 2 to 5 mol/mol. In multistage reactors, this applies to every intermediate feed of oxygenous and any hydrogenous gas.

[0036] The hydrogen is combusted catalytically. The dehydrogenation catalyst used generally also catalyzes the combustion of the hydrocarbons and of hydrogen with oxygen, so that in principle no specialized oxidation catalyst is required apart from it. In one embodiment, operation is effected in the presence of one or more oxidation catalysts which selectively catalyze the combustion of hydrogen with oxygen to water in the presence of hydrocarbons. The combustion of these hydrocarbons with oxygen to

give CO, CO₂ and water therefore proceeds only to a minor extent. The dehydrogenation catalyst and the oxidation catalyst are preferably present in different reaction zones.

[0037] When the reaction is carried out in more than one stage, the oxidation catalyst may be present only in one, in more than one or in all reaction zones.

[0038] Preference is given to disposing the catalyst which selectively catalyzes the oxidation of hydrogen at the points where there are higher partial oxygen pressures than at other points in the reactor, in particular near the feed point for the oxygenous gas. The oxygenous gas and/or hydrogenous gas may be fed in at one or more points in the reactor.

[0039] In one embodiment of the process according to the invention, there is intermediate feeding of oxygenous gas and of hydrogenous gas upstream of each tray of a tray reactor. In a further embodiment of the process according to the invention, oxygenous gas and hydrogenous gas are fed in upstream of each tray except the first tray. In one embodiment, a layer of a specialized oxidation catalyst is present downstream of every feed point, followed by a layer of the dehydrogenation catalyst. In a further embodiment, no specialized oxidation catalyst is present. The dehydrogenation temperature is generally from 400 to 1100°C, the pressure in the last catalyst bed of the tray reactor is generally from 0.2 to 5 bar, preferably from 1 to 3 bar. The GHSV is generally from 500 to 2000 h⁻¹, and in high-load operation, even up to 100 000 h⁻¹, preferably from 4000 to 16 000 h⁻¹.

[0040] A preferred catalyst which selectively catalyzes the combustion of hydrogen comprises oxides and/or phosphates selected from the group consisting of the oxides and/or phosphates of germanium, tin, lead, arsenic, antimony and bismuth. A further preferred catalyst which catalyzes the combustion of hydrogen comprises a noble metal of transition group VIII and/or I of the periodic table.

[0041] The dehydrogenation catalysts used generally comprise a support and an active composition. The support generally consists of a heat-resistant oxide or mixed oxide. The dehydrogenation catalysts preferably comprise a metal oxide selected from the group consisting of zirconium oxide, zinc oxide, aluminum oxide, silicon dioxide, titanium dioxide, magnesium oxide, lanthanum oxide, cerium oxide and mixtures thereof, as a support. The mixtures may be physical mixtures or else chemical

mixed phases such as magnesium aluminum oxide or zinc aluminum oxide mixed oxides. Preferred supports are zirconium dioxide and/or silicon dioxide, and particular preference is given to mixtures of zirconium dioxide and silicon dioxide.

[0042] The active composition of the dehydrogenation catalysts generally comprises one or more elements of transition group VIII of the periodic table, preferably platinum and/or palladium, more preferably platinum. Furthermore, the dehydrogenation catalysts may comprise one or more elements of main group I and/or II of the periodic table, preferably potassium and/or cesium. The dehydrogenation catalysts may further comprise one or more elements of transition group III of the periodic table including the lanthanides and actinides, preferably lanthanum and/or cerium. Finally, the dehydrogenation catalysts may comprise one or more elements of main group III and/or IV of the periodic table, preferably one or more elements selected from the group consisting of boron, gallium, silicon, germanium, tin and lead, more preferably tin.

[0043] In a preferred embodiment, the dehydrogenation catalyst comprises at least one element of transition group VIII, at least one element of main group I and/or II, at least one element of main group III and/or IV and at least one element of transition group III including the lanthanides and actinides.

[0044] For example, all dehydrogenation catalysts which are disclosed by WO 99/46039, US 4,788,371, EP-A 705 136, WO 99/29420, US 5,220,091, US 5,430,220, US 5,877,369, EP 0 117 146, DE-A 199 37 106, DE-A 199 37 105 and DE-A 199 37 107 may be used according to the invention. Particularly preferred catalysts for the above-described variants of autothermal n-butane dehydrogenation are the catalysts according to examples 1, 2, 3 and 4 of DE-A 199 37 107.

[0045] Preference is given to carrying out the n-butane dehydrogenation in the presence of steam. The added steam serves as a heat carrier and supports the gasification of organic deposits on the catalysts, which counteracts carbonization of the catalysts and increases the onstream time of the catalysts. The organic deposits are converted to carbon monoxide, carbon dioxide and in some cases water.

[0046] The dehydrogenation catalyst may be regenerated in a manner known per se. For instance, steam may be added to the reaction gas mixture or an oxygenous gas may be passed from time to time over the catalyst bed at elevated temperature

and the deposited carbon burnt off. Dilution with steam shifts the equilibrium toward the products of dehydrogenation. After the regeneration, the catalyst is optionally reduced with a hydrogenous gas.

[0047] The nonoxidative catalytic n-butane dehydrogenation provides a gas mixture which, in addition to butadiene, 1-butene, 2-butene and unconverted n-butane, comprises secondary constituents. Customary secondary constituents include hydrogen, steam, nitrogen, CO and CO₂, methane, ethane, ethene, propane and propene. The composition of the gas mixture leaving the first dehydrogenation zone may be highly variable depending on the dehydrogenation method. For instance, in the preferred autothermal dehydrogenation with feeding in of oxygen and additional hydrogen, the product gas mixture comprises a comparatively high content of steam and carbon oxides. In methods without feeding in of oxygen, the product gas mixture of the nonoxidative dehydrogenation has a comparatively high hydrogen content.

[0048] The product gas stream of the nonoxidative autothermal n-butane dehydrogenation typically contains from 0.1 to 15% by volume of butadiene, from 1 to 15% by volume of 1-butene, from 1 to 25% by volume of 2-butene (cis/trans-2-butene), from 20 to 70% by volume of n-butane, from 1 to 70% by volume of steam, from 0 to 10% by volume of low-boiling hydrocarbons (methane, ethane, ethene, propane and propene), from 0.1 to 40% by volume of hydrogen, from 0 to 70% by volume of nitrogen and from 0 to 5% by volume of carbon oxides.

[0049] The product gas stream b leaving the first dehydrogenation zone is preferably separated into two substreams, of which only one of the two substreams is subjected to the further process parts C to G and the second substream may be recycled into the first dehydrogenation zone. An appropriate procedure is described in DE-A 102 11 275. However, the entire product gas stream b of the nonoxidative catalytic n-butane dehydrogenation may also be subjected to the further process parts C to G.

[0050] According to the invention, the nonoxidative catalytic dehydrogenation is followed downstream by an oxidative dehydrogenation (oxydehydrogenation) as process part C. This substantially dehydrogenates 1-butene and 2-butene to 1,3-butadiene, and 1-butene is generally virtually fully depleted.

[0051] This may in principle be carried out in all reactor types and methods disclosed by the prior art, for example in a fluidized bed, in a tray furnace, in a fixed bed tubular or tube bundle reactor, or in a plate heat exchanger reactor. To carry out the oxidative dehydrogenation, a gas mixture is required which has a molar oxygen : n-butenes ratio of at least 0.5. Preference is given to working at an oxygen : n-butenes ratio of from 0.55 to 50. To attain this value, the product gas mixture stemming from the nonoxidative catalytic dehydrogenation is mixed with oxygen or an oxygenous gas, for example air. The resulting oxygenous gas mixture is then fed to the oxydehydrogenation.

[0052] The catalysts which are particularly suitable for the oxydehydrogenation are generally based on an Mo-Bi-O multimetal oxide system which generally additionally comprises iron. In general, the catalyst system also comprises additional components from groups 1 to 15 of the periodic table, for example potassium, magnesium, zirconium, chromium, nickel, cobalt, cadmium, tin, lead, germanium, lanthanum, manganese, tungsten, phosphorus, cerium, aluminum or silicon.

[0053] Suitable catalysts and their preparation are described, for example, in US 4,423,281 ($\text{Mo}_{12}\text{BiNi}_8\text{Pb}_{0.5}\text{Cr}_3\text{K}_{0.2}\text{O}_x$ and $\text{Mo}_{12}\text{Bi}_b\text{Ni}_7\text{Al}_3\text{Cr}_{0.5}\text{K}_{0.5}\text{O}_x$), US 4,336,409 ($\text{Mo}_{12}\text{BiNi}_6\text{Cd}_2\text{Cr}_3\text{P}_{0.5}\text{O}_x$), DE-A 26 00 128 ($\text{Mo}_{12}\text{BiNi}_{0.5}\text{Cr}_3\text{P}_{0.5}\text{Mg}_{7.5}\text{K}_{0.1}\text{O}_x + \text{SiO}_2$) and DE-A 24 40 329 ($\text{Mo}_{12}\text{BiCo}_{4.5}\text{Ni}_{2.5}\text{Cr}_3\text{P}_{0.5}\text{K}_{0.1}\text{O}_x$).

[0054] The stoichiometry of the active composition of a multitude of multimetal oxide catalysts suitable for the oxydehydrogenation can be encompassed under the general formula (I)



where the variables are defined as follows:

$X^1 =$	W, Sn, Mn, La, Ce, Ge, Ti, Zr, Hf, Nb, P, Si, Sb, Al, Cd and/or Mg;
$a =$	from 0.5 to 5, preferably from 0.5 to 2;
$b =$	from 0 to 5, preferably from 2 to 4;
$c =$	from 0 to 10, preferably from 3 to 10;
$d =$	from 0 to 10;
$e =$	from 0 to 10, preferably from 0.1 to 4;
$f =$	from 0 to 5, preferably from 0.1 to 2;

g = from 0 to 2, preferably from 0.01 to 1; and
 x = a number which is determined by the valency and frequency of the elements in (I) other than oxygen.

[0055] In the process according to the invention, preference is given to using an Mo-Bi-Fe-O multimetal oxide system for the oxydehydrogenation, and particular preference is given to an Mo-Bi-Fe-Cr-O or Mo-Bi-Fe-Zr-O metal oxide system. Preferred systems are described, for example, in US 4,547,615 ($\text{Mo}_{12}\text{BiFe}_{0.1}\text{Ni}_8\text{ZrCr}_3\text{K}_{0.2}\text{O}_x$ and $\text{Mo}_{12}\text{BiFe}_{0.1}\text{Ni}_8\text{AlCr}_3\text{K}_{0.2}\text{O}_x$), US 4,424,141 ($\text{Mo}_{12}\text{BiFe}_3\text{Co}_{4.5}\text{Ni}_{2.5}\text{P}_{0.5}\text{K}_{0.1}\text{O}_x + \text{SiO}_2$), DE-A 25 30 959 ($\text{Mo}_{12}\text{BiFe}_3\text{Co}_{4.5}\text{Ni}_{2.5}\text{Cr}_{0.5}\text{K}_{0.1}\text{O}_x$, $\text{Mo}_{13.75}\text{BiFe}_3\text{Co}_{4.5}\text{Ni}_{2.5}\text{Ge}_{0.5}\text{K}_{0.8}\text{O}_x$, $\text{Mo}_{12}\text{BiFe}_3\text{Co}_{4.5}\text{Ni}_{2.5}\text{Mn}_{0.5}\text{K}_{0.1}\text{O}_x$ and $\text{Mo}_{12}\text{BiFe}_3\text{Co}_{4.5}\text{Ni}_{2.5}\text{La}_{0.5}\text{K}_{0.1}\text{O}_x$), US 3,911,039 ($\text{Mo}_{12}\text{BiFe}_3\text{Co}_{4.5}\text{Ni}_{2.5}\text{Sn}_{0.5}\text{K}_{0.1}\text{O}_x$), DE-A 25 30 959 and DE-A 24 47 825 ($\text{Mo}_{12}\text{BiFe}_3\text{Co}_{4.5}\text{Ni}_{2.5}\text{W}_{0.5}\text{K}_{0.1}\text{O}_x$). The preparation and characterization of the catalysts mentioned are described comprehensively in the documents cited.

[0056] The oxydehydrogenation catalyst is generally used as shaped bodies having an average size of over 2 mm. Owing to the pressure drop to be observed when performing the process, smaller shaped bodies are generally unsuitable. Examples of useful shaped bodies include tablets, cylinders, hollow cylinders, rings, spheres, strands, wagon wheels or extrudates. Special shapes, for example "trilobes" and "tristars" (see EP-A-0 593 646) or shaped bodies having at least one notch on the exterior (see US 5,168,090) are likewise possible.

[0057] In general, the catalyst used may be used as an unsupported catalyst. In this case, the entire shaped catalyst body consists of the active composition, including any auxiliary, such as graphite or pore former and also further components. In particular, it has proven advantageous to use the Mo-Bi-Fe-O catalyst preferably used for the oxydehydrogenation of n-butenes to butadiene as an unsupported catalyst. Furthermore, it is possible to apply the active compositions of the catalysts to a support, for example an inorganic, oxidic shaped body. Such catalysts are generally referred to as coated catalysts.

[0058] The oxydehydrogenation is generally carried out at a temperature of from 220 to 490°C and preferably from 250 to 450°C. A reactor entrance pressure is selected which is sufficient to overcome the flow resistances in the plant and the subsequent workup. This reactor entrance pressure is generally from 0.005 to 1 MPa

above atmospheric pressure, preferably from 0.01 to 0.5 MPa above atmospheric pressure. By its nature, the gas pressure applied in the entrance region of the reactor substantially falls over the entire catalyst bed.

[0059] The coupling of the nonoxidative catalytic, preferably autothermal, dehydrogenation with the oxidative dehydrogenation of the n-butenes formed provides a very much higher yield of butadiene based on n-butane used. The nonoxidative dehydrogenation can also be operated in a gentler manner. Comparable butadiene yields would only be achievable with an exclusively nonoxidative dehydrogenation at the cost of distinctly reduced selectivities. An exclusively oxidative dehydrogenation only achieves low n-butane conversions.

[0060] In addition to butadiene and unconverted n-butane, the product gas stream c leaving the oxidative dehydrogenation comprises 2-butene and steam. As secondary constituents it generally comprises carbon monoxide, carbon dioxide, oxygen, nitrogen, methane, ethane, ethene, propane and propene, with or without hydrogen and also oxygenous hydrocarbons, known as oxygenates. In general, it only comprises very small proportions of 1-butene.

[0061] In general, the product gas stream c leaving the oxidative dehydrogenation has from 1 to 40% by volume of butadiene, from 20 to 80% by volume of n-butane, from 0.5 to 40% by volume of 2-butene, from 0 to 5% by volume of 1-butene, from 0 to 70% by volume of steam, from 0 to 10% by volume of low-boiling hydrocarbons (methane, ethane, ethene, propane and propene), from 0.1 to 40% by volume of hydrogen, from 0 to 70% by volume of nitrogen, from 0 to 10% by volume of carbon oxides and from 0 to 10% by volume of oxygenates. Oxygenates may be, for example, furan, acetic acid, maleic anhydride, formic acid and butyraldehyde.

[0062] In one process part, D, low-boiling secondary constituents other than the C₄ hydrocarbons (n-butane, isobutane, 1-butene, cis-/trans-2-butene, isobutene, butadiene) are at least partly, but preferentially substantially completely, removed from the product gas stream of the n-butane dehydrogenation to obtain a C₄ product gas stream d.

[0063] In one embodiment of the process according to the invention, water is initially removed from the product gas stream c in process part D. Water may be removed, for example, by condensing out by cooling and/or compressing the product

gas stream c, and may be carried out in one or more cooling and/or compression stages.

[0064] The low-boiling secondary constituents may be removed from the product gas stream by customary separation processes such as distillation, rectification, membrane processes, absorption or adsorption.

[0065] To remove the hydrogen present in the product gas stream c, the product gas mixture, if appropriate on completion of cooling, is passed through a membrane, generally configured as a tube, which is permeable only to molecular hydrogen, for example in an indirect heat exchanger. The thus removed molecular hydrogen may, if required, be used at least partly in the dehydrogenation or else sent to another utilization, for example for generating electrical energy in fuel cells.

[0066] The carbon dioxide present in the product gas stream c may be removed by CO₂ gas scrubbing. The carbon dioxide gas scrubbing may be preceded upstream by a separate combustion stage in which carbon monoxide is selectively oxidized to carbon dioxide.

[0067] In a preferred embodiment of the process according to the invention, the uncondensable or low-boiling gas constituents such as hydrogen, oxygen, carbon oxides, the low-boiling hydrocarbons (methane, ethane, ethene, propane, propene) and any nitrogen are removed by means of a high-boiling absorbent in an absorption/desorption cycle to obtain a C₄ product gas stream c which consists substantially of the C₄ hydrocarbons. In general, at least 80% by volume, preferably at least 90% by volume, more preferably at least 95% by volume, of the C₄ product gas stream c consists of the C₄ hydrocarbons. The stream d consists substantially of n-butane, 2-butene and butadiene.

[0068] To this end, in an absorption stage, the product gas stream c, after preceding water removal, is contacted with an inert absorbent and the C₄ hydrocarbons are absorbed in the inert absorbent to obtain absorbent laden with C₄ hydrocarbons and an offgas comprising the remaining gas constituents. In a desorption stage, the C₄ hydrocarbons are released again from the absorbent.

[0069] Inert absorbents used in the absorption stage are generally high-boiling nonpolar solvents in which the C₄ hydrocarbon mixture to be removed has a distinctly

higher solubility than the remaining gas constituents to be removed. The absorption may be effected by simply passing the product gas stream c through the absorbent. However, it may also be effected in columns or in rotary absorbers. Operation may be effected in cocurrent, countercurrent or crosscurrent. Examples of suitable absorption columns include tray columns having bubble-cap, centrifugal and/or sieve trays, columns having structured packings, for example sheet metal packings having a specific surface area of from 100 to 1000 m²/m³ such as Mellapak® 250 Y, and randomly packed columns. However, useful absorption columns also include trickle and spray towers, graphite block absorbers, surface absorbers such as thick-film and thin-film absorbers and also rotary columns, plate scrubbers, cross-spray scrubbers and rotary scrubbers.

[0070] Suitable absorbents are comparatively nonpolar organic solvents, for example aliphatic C₆- to C₁₈-alkenes, or aromatic hydrocarbons such as the middle oil fractions from paraffin distillation, or ethers having bulky groups, or mixtures of these solvents, to each of which a polar solvent such as 1,2-dimethyl phthalate may be added. Further suitable absorbents include esters of benzoic acid and phthalic acid with straight-chain C₁-C₈-alkanols, such as n-butyl benzoate, methyl benzoate, ethyl benzoate, dimethyl phthalate, diethyl phthalate, and also heat carrier oils, such as biphenyl and diphenyl ether, their chlorine derivatives and also triarylalkenes. A useful absorbent is a mixture of biphenyl and diphenyl ether, preferably in the azeotropic composition, for example the commercially available Diphyl®. Frequently, this solvent mixture contains dimethyl phthalate in an amount of 0.1 to 25% by weight. Further suitable absorbents are octanes, nonanes, decanes, undecanes, dodecanes, tridecanes, tetradecanes, pentadecanes, hexadecanes, heptadecanes and octadecanes, or fractions obtained from refinery streams which have the linear alkanes mentioned as main components.

[0071] For desorption of the C₄ hydrocarbons, the laden absorbent is heated and/or decompressed to a lower pressure. Alternatively, desorption may also be effected by stripping or in a combination of decompression, heating and stripping in one or more process steps. The absorbent regenerated in the desorption stage is recycled into the absorption stage.

[0072] In one process step, the desorption step is carried out by decompressing and/or heating the laden desorbent.

[0073] The removal D is generally not entirely complete, so that, depending on the type of removal, small amounts or even only traces of the further gas constituents, especially of the low-boiling hydrocarbons, may still be present in the C₄ product gas stream.

[0074] The volume flow reduction brought about by the removal D also deburdens the downstream process steps.

[0075] The C₄ product gas stream d consisting substantially of n-butane, 2-butene and butadiene contains generally from 20 to 80% by volume of butadiene, from 20 to 80% by volume of n-butane and from 0 to 50% by volume of 2-butene.

[0076] In one process part, E, the C₄ product gas stream d is separated by extractive distillation into a recycle stream e1 consisting substantially of n-butane and 2-butene and a stream e2 consisting substantially of butadiene. The stream e1 is recycled into the first dehydrogenation zone.

[0077] The extractive distillation may be carried out, for example, as described in Erdöl und Kohle – Erdgas – Petrochemie [Mineral Oil and Coal – Natural Gas – Petrochemistry] volume 34 (8), pages 343 – 346 or Ullmanns Enzyklopädie der Technischen Chemie, volume 9, 4th edition 1975, pages 1 to 18.

[0078] To this end, the C₄ product gas stream d is contacted in an extraction zone with an extractant, preferably an N-methylpyrrolidone (NMP)/water mixture. The extraction zone is generally configured in the form of a wash column which comprises trays, random packings or structured packings as internals. It generally has from 30 to 70 theoretical plates, so that sufficiently good separating action is achieved. The wash column preferably has a backwash zone in the top of the column. This backwash zone serves to recycle the extractant present in the gas phase by means of a liquid hydrocarbon reflux, for which the top fraction is condensed beforehand. Typical temperatures at the top of the column are between 30 and 60°C. The mass ratio of extractant to C₄ product gas stream d in the feed of the extraction zone is generally from 10 : 1 to 20 : 1.

[0079] Suitable extractants are butyrolactone, nitriles such as acetonitrile, propionitrile, methoxypropionitrile, ketones such as acetone, furfural, N-alkyl-substituted lower aliphatic amides such as dimethylformamide, diethylformamide,

dimethylacetamide, diethylacetamide, N-formylmorpholine, N-alkyl-substituted cyclic amides (lactams) such as N-alkylpyrrolidones, especially N-methylpyrrolidone (NMP). In general, alkyl-substituted lower aliphatic amides or N-alkyl-substituted cyclic amides are used. Particularly advantageous are dimethylformamide, acetonitrile, furfural and especially NMP.

[0080] However, it is also possible to use mixtures of these extractants with one another, for example of NMP and acetonitrile, mixtures of these extractants with cosolvents and/or tert-butyl ethers, e.g. methyl tert-butyl ether, ethyl tert-butyl ether, propyl tert-butyl ether, n- or isobutyl tert-butyl ether. Particularly suitable is NMP, preferably in aqueous solution, preferably with from 0 to 20% by weight of water, more preferably with from 7 to 10% by weight of water, in particular with 8.3% by weight of water.

[0081] In the extraction zone, a gaseous stream e1 consisting substantially of n-butane and 2-butene and an extraction solution comprising butadiene are formed. In general, the stream e1 consisting substantially of n-butane and 2-butene contains from 50 to 100% by volume of n-butane, from 0 to 50% by volume of 2-butene and from 0 to 3% by volume of further constituents such as isobutane, isobutene, propane, propene and C₅⁺ hydrocarbons.

[0082] The extraction solution is transferred into a desorption zone having reduced pressure and/or elevated temperature compared to the extraction zone, and the butadiene is desorbed from the extraction solution. The desorption zone may be configured, for example, in the form of a wash column which has from 5 to 15, preferably from 8 to 10, theoretical plates, and a backwash zone having, for example, 4 theoretical plates. This backwash zone serves to recover the extractant present in the gas phase by means of liquid hydrocarbon reflux, for which the top fraction is condensed beforehand. The internals provided are structured packings, trays or random packings. The pressure at the top of the column is, for example, 1.5 bar. The temperature in the bottom of the column is, for example, from 130 to 150°C.

[0083] The product of value stream e2 obtained at the top of the column generally contains from 90 to 100% by volume of butadiene, from 0 to 10% by volume of 2-butene and from 0 to 10% by volume of n-butane and isobutane.

[0084] In one embodiment of the process according to the invention, in a further process part, F, the stream e2 consisting substantially of butadiene is fed into a selective hydrogenation zone and butadiene is hydrogenated to 1- and/or 2-butene to obtain a stream f comprising 1-butene and 2-butene.

[0085] The stream e2 consisting substantially of butadiene may be fed fully or partly into the selective hydrogenation zone. It is thus possible to variably control the amounts of butadiene and 1-butene obtained and adapt them to the demand at any time.

[0086] The selective hydrogenation may be carried out in a manner known per se in the gas phase, liquid phase or trickle phase. Preference is given to carrying out the selective hydrogenation in the liquid or trickle phase with fixed bed hydrogenation catalyst. The hydrogenation catalysts used may be supported noble metal catalysts which comprise palladium, platinum, silver, gold, rhodium, ruthenium, osmium or mixtures of these metals. Particularly preferred hydrogenation catalysts are supported catalysts comprising palladium. A hydrogenation catalyst used with preference is described, for example, in EP-A 0 992 284. This comprises metals of group 8, 9 and 10 of the periodic table, especially ruthenium, rhodium, palladium and/or platinum, on an alumina support and additionally at least one metal of group 11 of the periodic table, preferably copper and/or silver. The content of metal of group 8, 9 or 10 of the periodic table in the catalyst is generally from 0.05 to 2% by weight, preferably from 0.1 to 0.5% by weight.

[0087] The selective hydrogenation may be carried out in one or more reactors connected in series. The selective hydrogenation may be performed, for example, in two stages. The temperature is typically in the range from 0°C to 180°C and the pressure in the range from 2 to 50 bar. In one embodiment, the selective hydrogenation is carried out at a temperature of from 20 to 90°C and a pressure in the range from 5 to 50 bar, and from 1 to 1.5 mol of hydrogen are used per mole of butadiene.

[0088] The stream f leaving the selective hydrogenation zone comprises predominantly 1-butene and 2-butene and additionally n-butane. In general, the stream f contains from 20 to 80% by volume of 1-butene, from 20 to 80% by volume of 2-butene and from 0 to 10% by volume of n-butane. In addition, the stream f may also contain small amounts of further gas constituents such as isobutane, isobutene and

butadiene, generally in amounts of from 0 to 5% by volume, preferably from 0 to 1% by volume.

[0089] If appropriate, in a further process part, G, the stream f comprising substantially 1-butene and 2-butene is fed into a distillation zone. There, a product of value stream g1 consisting substantially of 1-butene and a recycle stream g2 comprising 2-butene are obtained. The recycle stream g2 is recycled into the first or second dehydrogenation zone. The product of value stream g1 is discharged from the process.

[0090] The distillation zone generally consists of a distillation column having generally from 30 to 80, preferably from 40 to 75, theoretical plates. Suitable are, for example, bubble-cap tray columns, columns having random packings or structured packings, or dividing wall columns. The reflux ratio is generally from 10 to 50. The distillation is generally carried out at a pressure of from 5 to 20 bar.

[0091] In the upper section of the column, preferably at the top of the column, a stream g1 consisting substantially of 1-butene is drawn off. This generally contains at least 90% by volume, preferably at least 95% by volume, of 1-butene and additionally up to 10% by volume, preferably up to 5% by volume, of further constituents such as n-butane, isobutane, isobutene, butadiene and 2-butene.

[0092] In the lower section of the column, preferably in the lower fifth of the column, more preferably at the bottom of the column up to a maximum of 5 theoretical plates above the bottom of the column, a stream g2 comprising 2-butene is drawn off. Typically, the stream g2 contains from 55 to 95% by volume of 2-butene and additionally from 0 to 30% by volume of n-butane and from 0 to 15% by volume of 1-butene. It is possible to remove a purge gas stream from the stream g2 comprising 2-butene in order to prevent the accumulation of high boilers.

Examples

[0093] Example 1

[0094] A feed gas stream (4) comprising n-butane, said stream being obtained by combining a fresh gas stream (1) and a recycle stream (12), is fed to the first, autothermally operated, nonoxidative catalytic n-butane dehydrogenation stage (BDH).

To provide the heat required for the endothermic dehydrogenation, hydrogen is combusted selectively and is fed together with the combustion air as stream (2). In order to counteract carbonization of the catalyst and prolong the onstream time of the catalyst, steam (3) is also added. A dehydrogenation gas mixture (5) is obtained, which is cooled after leaving the BDH and fed to the second, oxidative, n-butane dehydrogenation stage (ODH). Also fed to the ODH is an air stream (6). For BDH and ODH, based on experimental results, the degrees of conversion and selectivities reproduced in Table 1 were assumed.

Table 1

Reaction stage	Conversion [%]	Selectivity [%]
Autothermal dehydrogenation (BDH)	50.5 (n-butane)	98.4 (to butenes/butadiene)
Oxidative dehydrogenation (ODH)	100.0 (1-butene) 92.7(2-butene)	95.0 (to butadiene)

[0095] The exit gas (7) of the ODH is compressed with intermediate cooling in several stages. The aqueous condensate (8) obtained in the intermediate coolings is discharged from the process. The compressed butadienic gas (9) is fed to an absorption stage which is operated with tetradecane as an absorbent. In the absorption stage, an inert gas stream (10) is removed from the C₄ hydrocarbon stream (11). The C₄ hydrocarbon stream (11) is separated in an extractive distillation stage into a stream (13) consisting substantially of butadiene and a recycle stream (12) comprising predominantly n-butane.

[0096] The results of the simulation calculation are reproduced in Table 2. The composition of the streams (1) and (13) is reported in parts by volume.

[0097] Example 2

[0098] In addition to the process steps described in Example 1, the following process steps were also carried out: a substream (14) of the butadiene (13) obtained in the extractive distillation stage is fed to a selective hydrogenation stage and hydrogenated with hydrogen (18) to a mixture (15) of 1- and 2-butene. The stream (15)

composed of 1-butene and 2-butene is separated in a distillation stage into a product gas stream (17) consisting substantially of 1-butene and a 2-butene-rich recycle stream (16) which is recycled back into the BDH together with the fresh gas stream (1) and the recycle stream (12).

[0099] The results of the simulation calculation are reproduced in Table 3. The composition of the streams is reported in parts by volume.

Table 2

Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Amount [kg/h]	24173	19242	1150	52279	72672	70378	143049	13929	129120	80264	48855	28105	20750
Propane	0.0000	0.0000	0.0000	0.0785	0.0363	0.0000	0.0167	0.0073	0.0184	0.0003	0.0813	0.1397	0.0000
Propene	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Butane	1.0000	0.0000	0.0000	0.8443	0.1729	0.0000	0.0794	0.0000	0.0939	0.0004	0.4208	0.7231	0.0000
1-Butene	0.0000	0.0000	0.0000	0.0000	0.0561	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2-Butene	0.0000	0.0000	0.0000	0.0165	0.1216	0.0000	0.0041	0.0054	0.0038	0.0000	0.0171	0.0294	0.0000
1,3-Butadiene	0.0000	0.0000	0.0000	0.0000	0.0115	0.0000	0.0789	0.0000	0.0934	0.0004	0.4181	0.0000	1.0000
Water	0.0000	0.0000	1.0000	0.0414	0.1566	0.0000	0.1610	0.9853	0.0102	0.0008	0.0428	0.0736	0.0000
Carbon dioxide	0.0000	0.0000	0.0000	0.0181	0.0106	0.0000	0.0204	0.0015	0.0238	0.0253	0.0187	0.0322	0.0000
Hydrogen	0.0000	0.2853	0.0000	0.0000	0.2019	0.0000	0.0927	0.0000	0.1096	0.1410	0.0000	0.0000	0.0000
Oxygen	0.0000	0.1429	0.0000	0.0007	0.0001	0.2100	0.0450	0.0001	0.0532	0.0682	0.0008	0.0013	0.0000
Nitrogen	0.0000	0.5718	0.0000	0.0004	0.2323	0.7900	0.5018	0.0002	0.5936	0.7635	0.0004	0.0006	0.0000
[°C]	25.0	25.0	150.0	500.0	550.0	115.0	400.0	55.0	55.0	35.0	50.0	40.0	40.0
Pressure [bar]	3.1	3.1	3.1	3.1	2.7	2.7	2.4	10.5	10.5	10.5	4.9	4.9	4.9

Table 3

Stream No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Amount [kg/h]	37793	29172	1771	98685	129629	115842	245470	22109	223361	131065	92296	55277	20750	16268	16875	5613	11261	606
Propane	0.0000	0.0000	0.0000	0.2055	0.1040	0.0000	0.0487	0.0149	0.0544	0.0007	0.2132	0.3472	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Propene	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Butane	1.0000	0.0000	0.0000	0.6723	0.1530	0.0000	0.0717	0.0000	0.0838	0.0004	0.3305	0.5383	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1-Butene	0.0000	0.0000	0.0000	0.0005	0.0582	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.6700	0.0100	0.9990	0.0000
2-Butene	0.0000	0.0000	0.0000	0.0700	0.1250	0.0000	0.0043	0.0042	0.0043	0.0001	0.0168	0.0273	0.0000	0.0000	0.3300	0.9900	0.0010	0.0000
1,3-Butadiene	0.0000	0.0000	0.0000	0.0000	0.0139	0.0000	0.0838	0.0000	0.0980	0.0007	0.3860	0.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0000
Water	0.0000	0.0000	1.0000	0.0267	0.1303	0.0000	0.1545	0.9795	0.0148	0.0104	0.0277	0.0452	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Carbon	0.0000	0.0000	0.0000	0.0239	0.0170	0.0000	0.0243	0.0012	0.0281	0.0293	0.0248	0.0405	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000